Recent Updates to the GEOS-5 Linear Model

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Introduction

GMAO is close to having a working 4DVAR system and has developed a linearized version of GEOS-5.

This talk outlines a series of improvements made to the linearized dynamics, physics and trajectory.

Of particular interest is the development of linearized cloud microphysics, which provides the framework for 'all-sky' data assimilation.

Outline

- Introduction
- Updated Dynamics
- Updated Boundary Layer
- Advection
- Moist Physics
- Radiation
- Gaussian Quadrature
- Sensitivity Studies

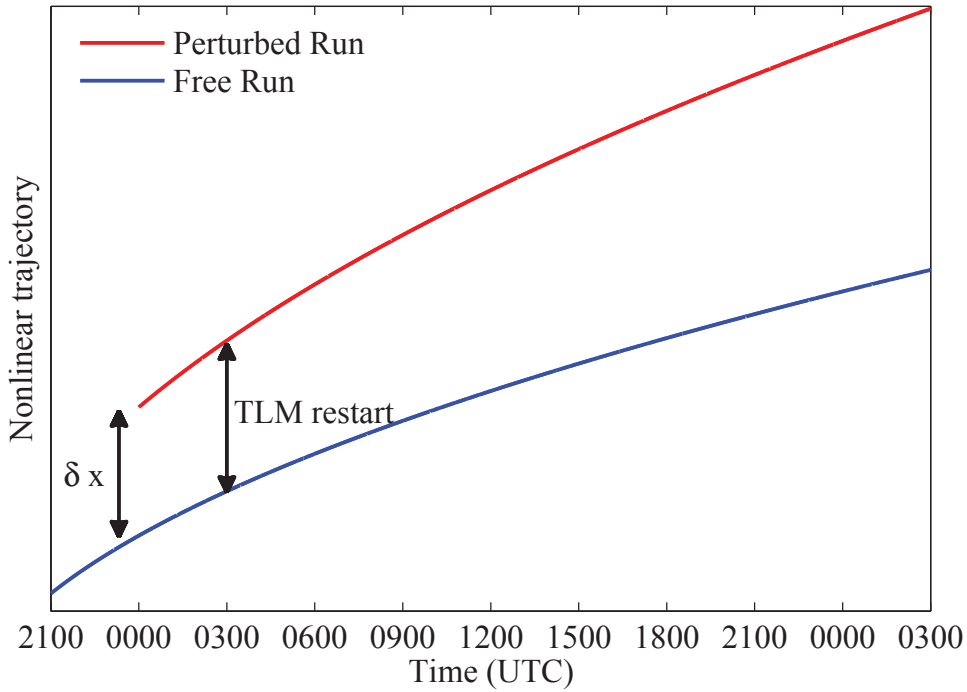
Metrics for improvement

The linear model is validated by comparing correlations, RMSE and RMS between the nonlinear perturbation trajectory,

$$\mathbf{m}(\mathbf{x} + \delta\mathbf{x}) - \mathbf{m}(\mathbf{x}),$$

and the tangent linear model perturbation trajectory,

$$\mathbf{M}\delta\mathbf{x},$$

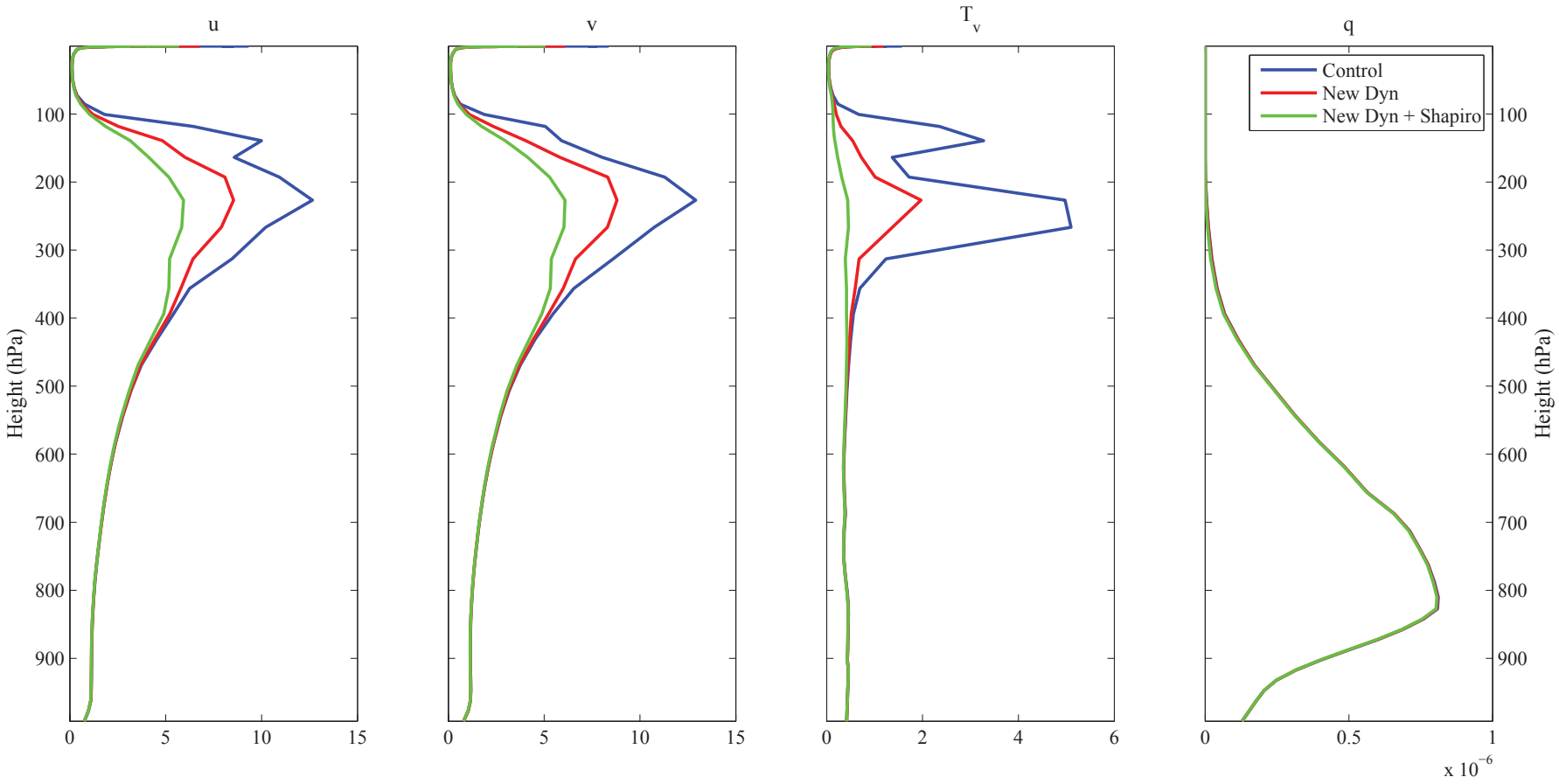


Updated Dynamics (Jong Kim)

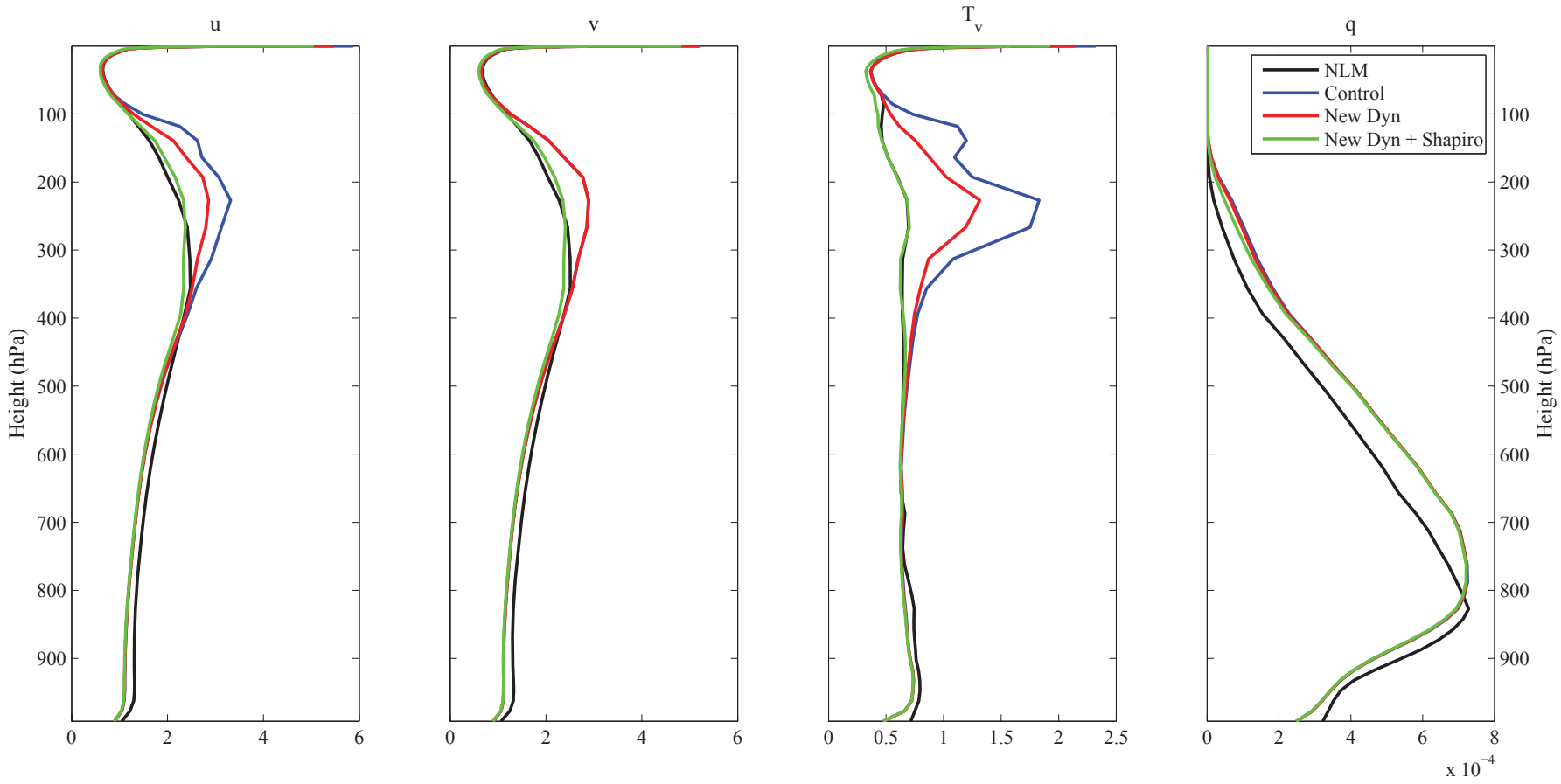
Noticed that with increased resolution the linear model has issues at the jet levels.

- Update to sponge levels to make more like NL model.
- Reduced 'KORD' in remapping (more stable and linear).
- Added option to apply Shapiro filter at the jet levels

Updated Dynamics - RMSD



Updated Dynamics - RMS



Updated Boundary Layer

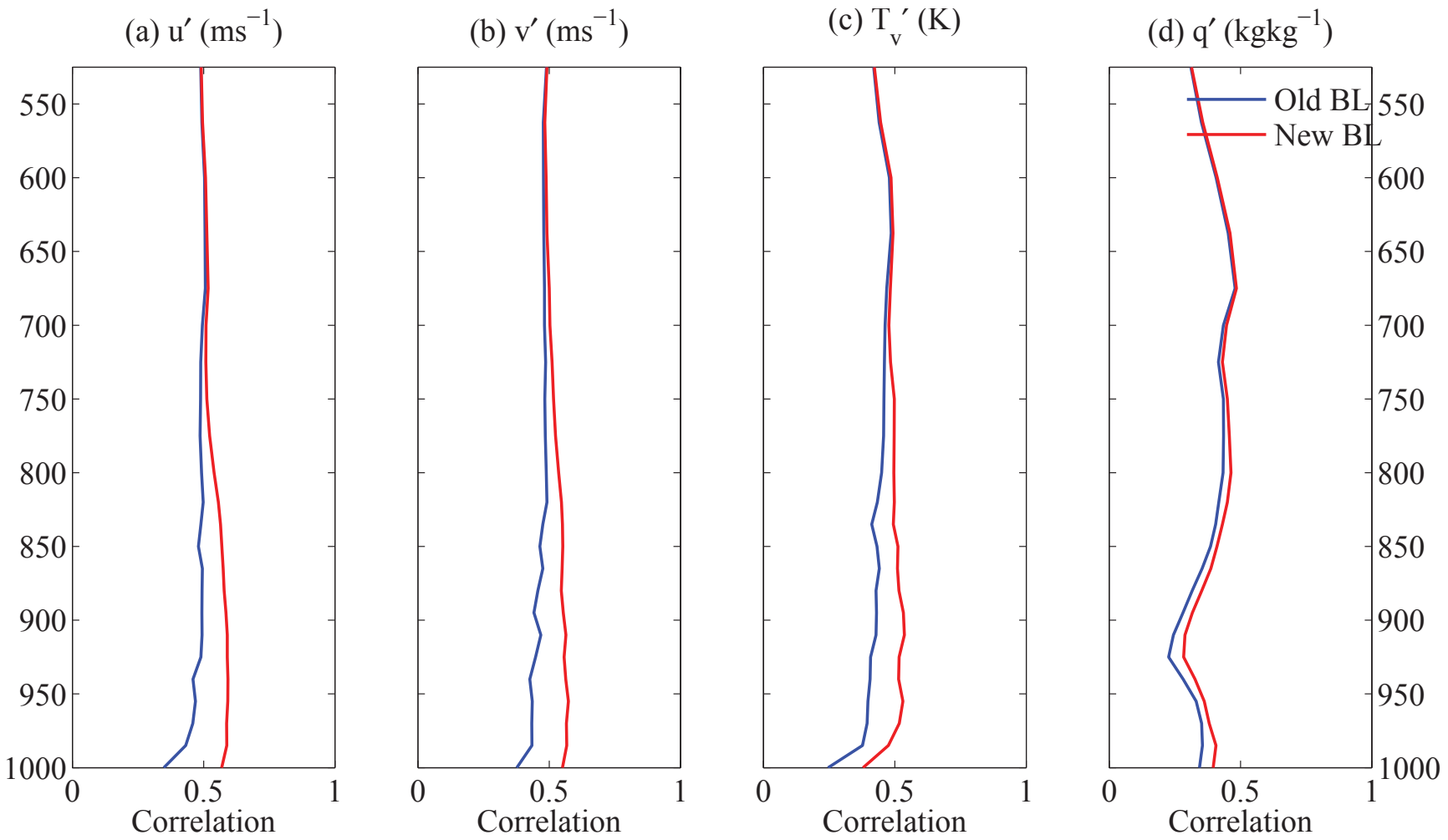
Originally a simple Louis type BL scheme was used in the linear model to stabilize the dynamics.

- Large correlation reduction near the surface for winds and temperature.
- Potential to upset the cloud scheme.

Updated to use the full $K_{m,h}^{(r)}$ that is used in the nonlinear model.

- Perturbations $K'_{m,h}$ still neglected to avoid steep gradients near stable-unstable ($R_i = 0$) transition.

Updated Boundary Layer - Correlations



Linearized Advection

Another aspect of the model that interacts strongly with prognostic clouds is the advection.

Tracers in linearized GEOS-5 advected with schemes used in nonlinear model.

- PPM of Colella and Woodward (1984)/Van Leer (1977)
- Uses Huynh 1996 second constraint and Lin 2004 RMC.

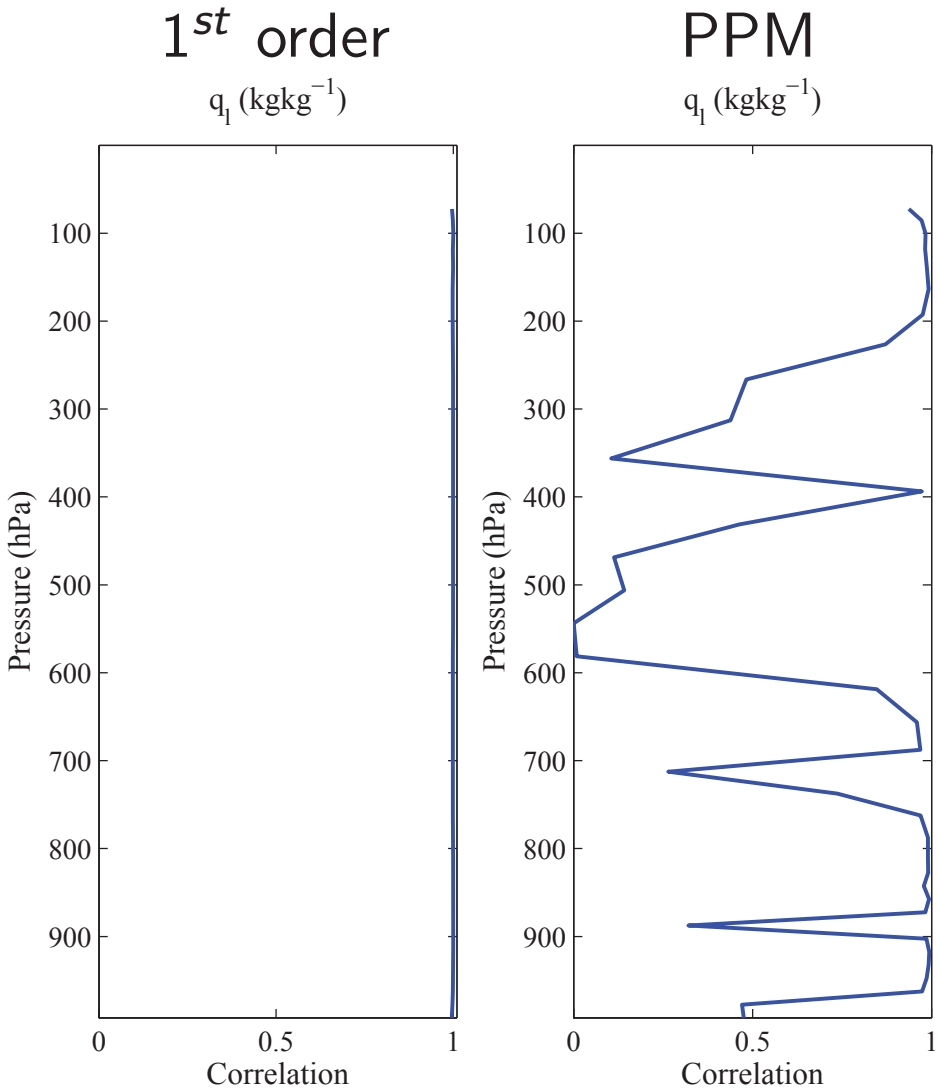
These schemes have the potential for nonlinearity.

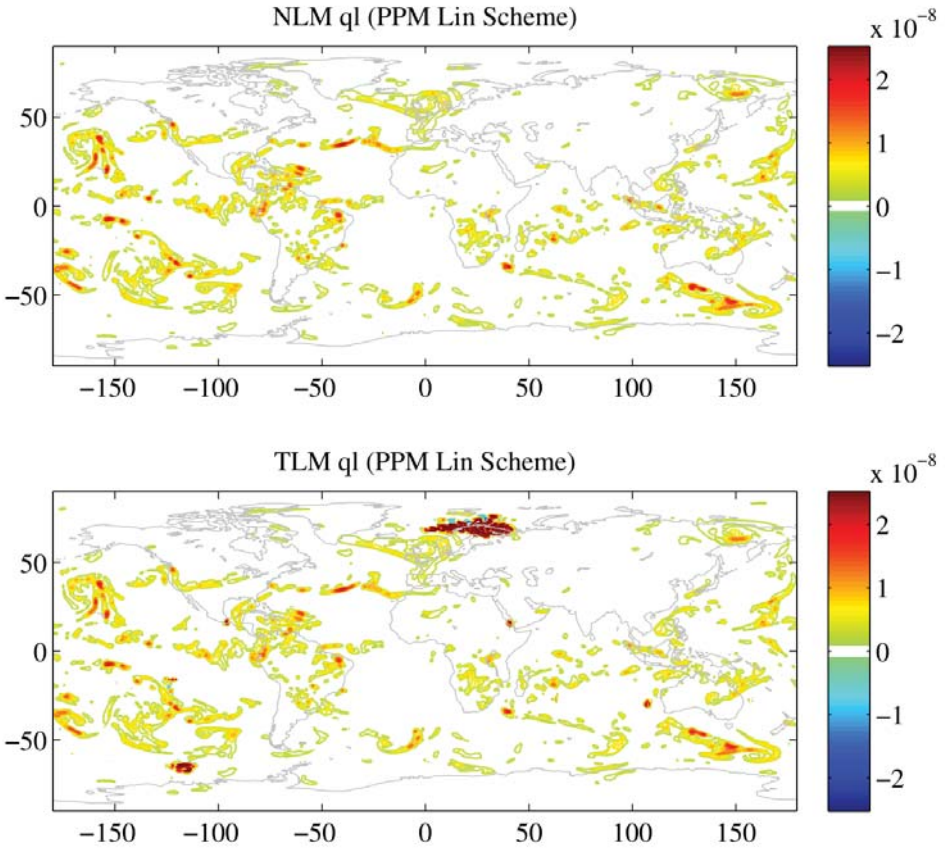
Passive cloud test

To test the tangent linear behavior of the advection we set up a passive cloud experiment.

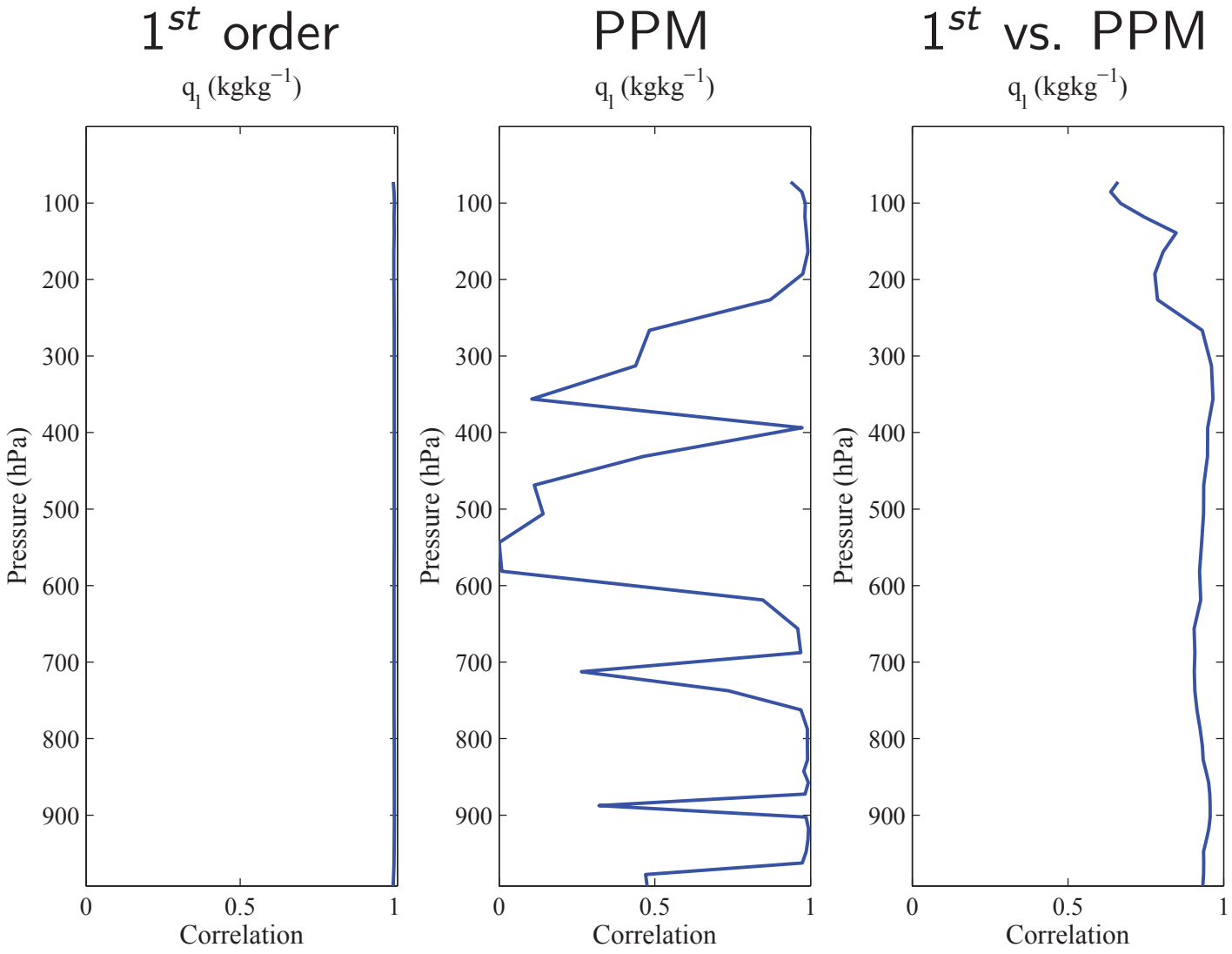
- Only perturbed variables are clouds.
- Perturbation is infinitesimal and has structure of field itself.
- Cloud uncoupled from other fields (GOCART and Radiation off).
- Wind is constant in time ($u' = 0$) so continuous advection is linear.

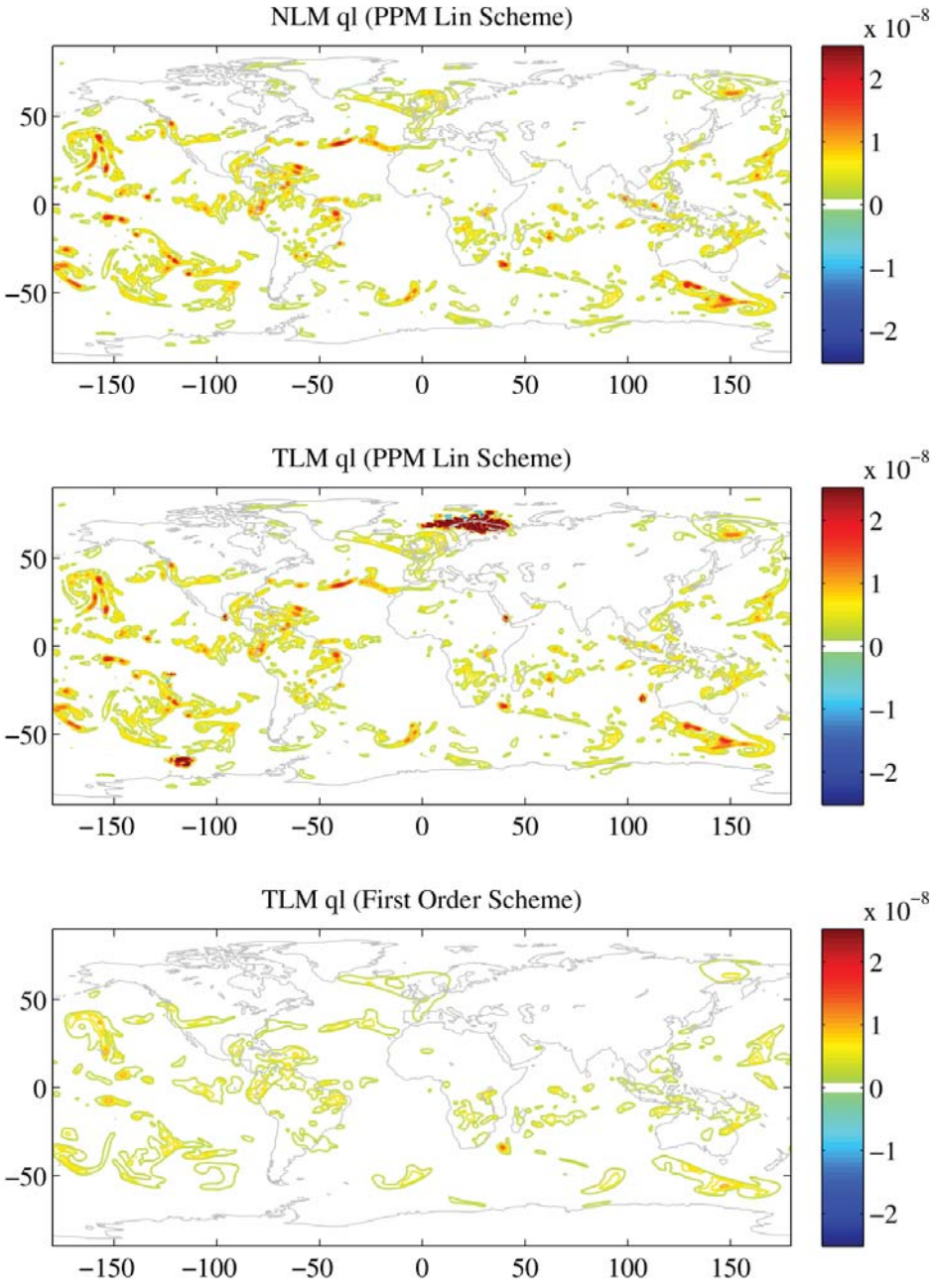
Passive cloud - correlations




NLM ql (PPM Lin Scheme)
x 10^-8
2
1
0
−1
−2
50
0
−50
−150
−100
−50
0
50
100
150
TLM ql (PPM Lin Scheme)
x 10^-8
2
1
0
−1
−2
50
0
−50
−150
−100
−50
0
50
100
150

Passive cloud - correlations



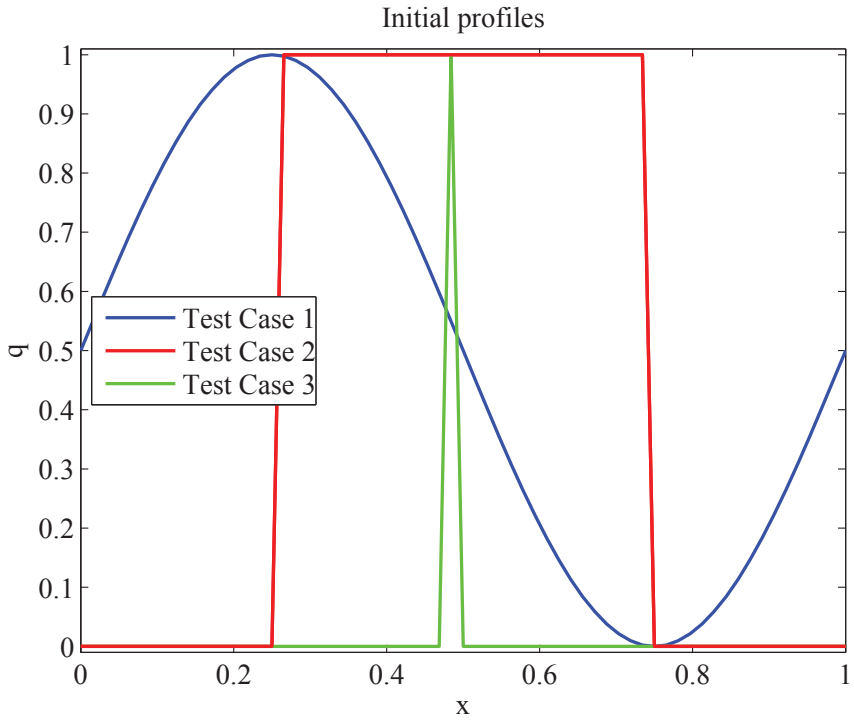

NLM ql (PPM Lin Scheme)
TLM ql (PPM Lin Scheme)
TLM ql (First Order Scheme)
x 10^-8
2
1
0
−1
−2
50
0
−50
−150
−100
−50
0
50
100
150

Advection 1D Case Study

We don't really want to put up with either of these situations so we're investigating further...

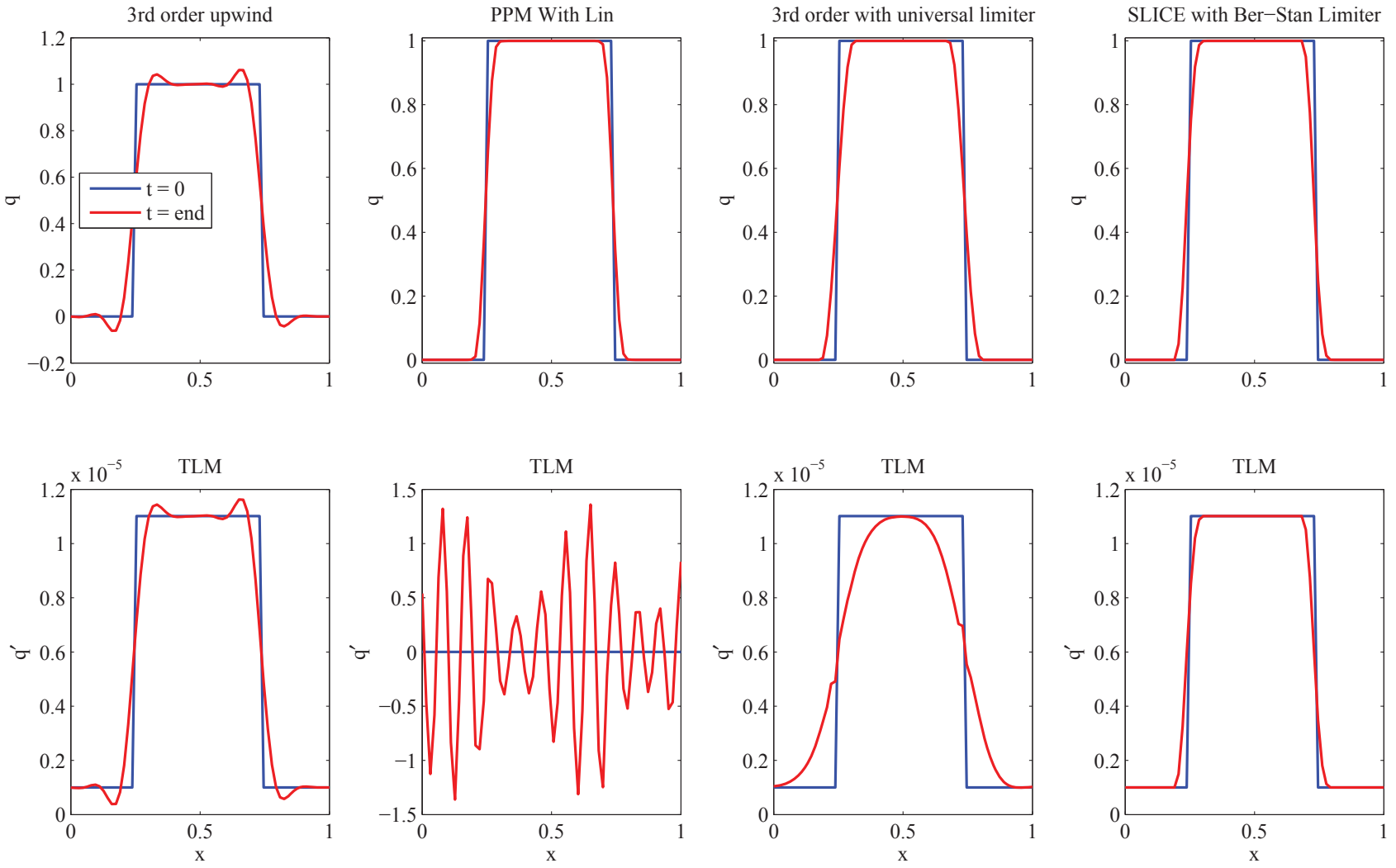
$$\frac{\partial q'}{\partial t} = u^{(r)} \frac{\partial q'}{\partial x},$$

$u^{(r)} = 1$, $x = (0, 1]$, $N = 64$, $\Delta x = 1/N$, $\Delta t = 0.1/N$. Three test cases.



Perturbations are initial profiles multiplied by 1×10^{-4}.

Advection 1D Case Study



Advection 1D Case Study

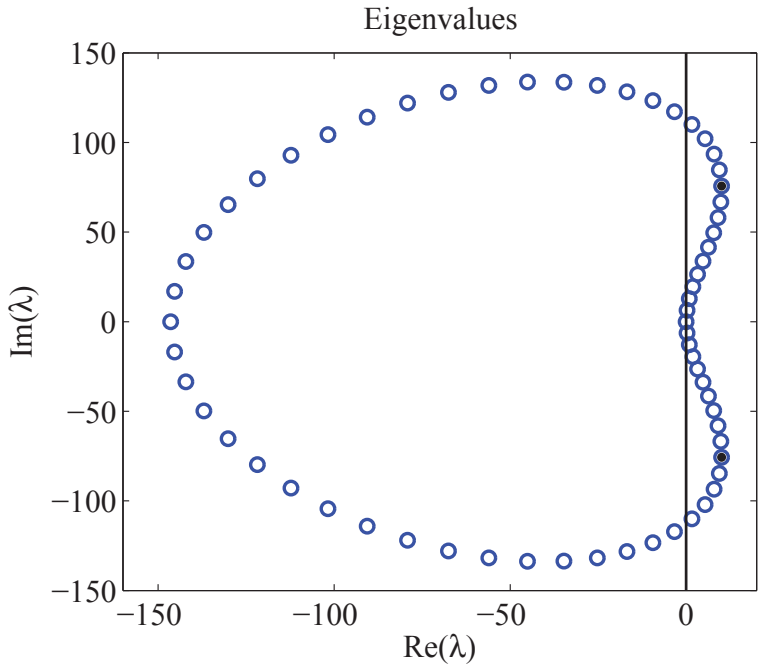
In Matrix form,

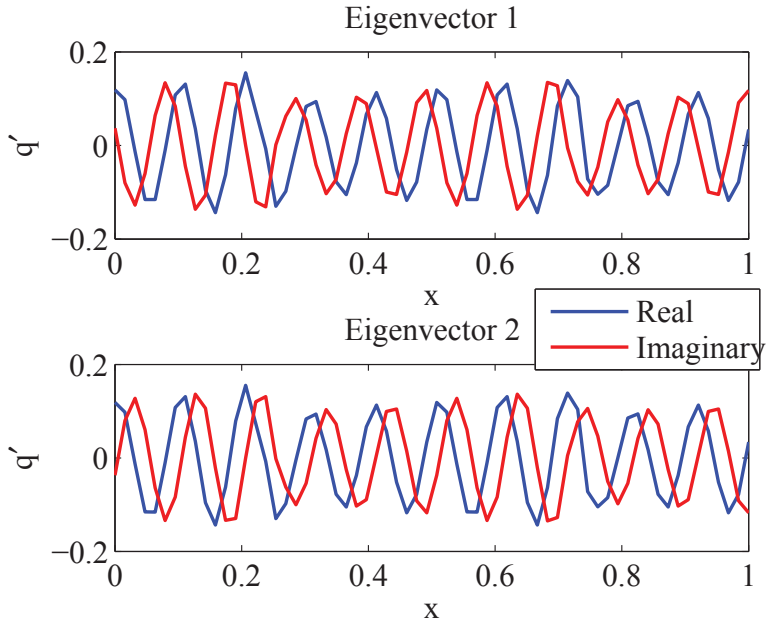
$$\dot{\mathbf{q}}' = \mathbf{A}\mathbf{q}',$$

Seek solution $q \sim \exp(-i\lambda t)$

$$-\lambda \mathbf{q}' = \mathbf{A}\mathbf{q}'.$$

Test case 2 PPM scheme:





Linearized cloud scheme

Linear cloud scheme to accompany recently implemented linear RAS scheme Holdaway et al (2014).

- Based on Bacmeister scheme used in nonlinear model.
- Single moment microphysics (mass mixing ratio).
- Prognostic treatment of clouds.
- Linear model variables q_l', q_i' and C_{AN}'.
- Cloud scheme variables $q_{l,LS}'$, $q_{l,AN}'$, $q_{i,LS}'$, $q_{i,AN}'$, C_{LS}' and C_{AN}'.
- Trajectory $q_{LS}^{(r)}$, $q_{AN}^{(r)}$ and $C_{AN}^{(r)}$.
- Sources using RAS & PDF approach, evaporation, sublimation, autoconversion and falling and reevaporation of precipitation.

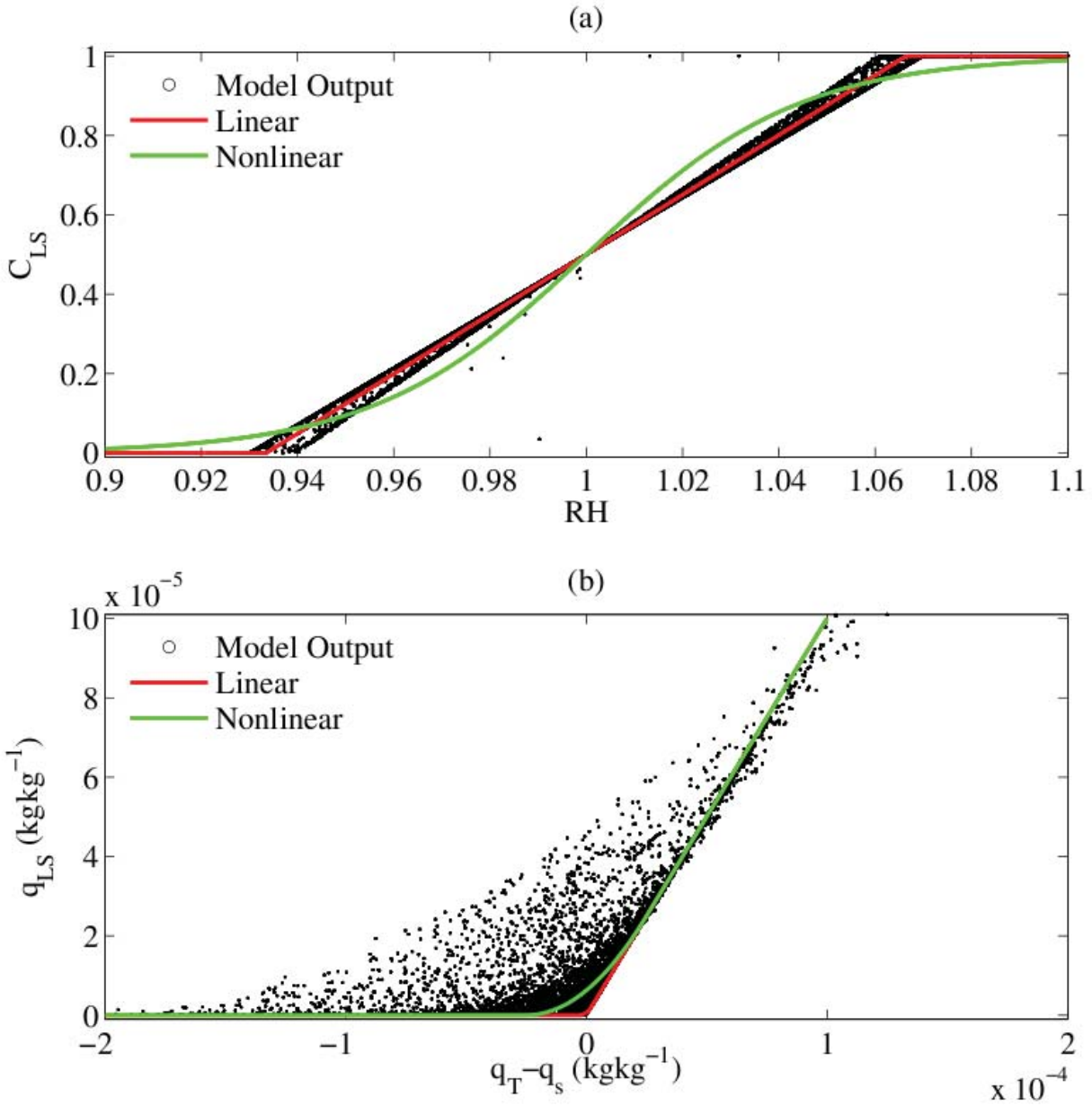
Problems in large scale cloud source

The cloud scheme uses many nonlinear functions with discontinuities and steep gradients.

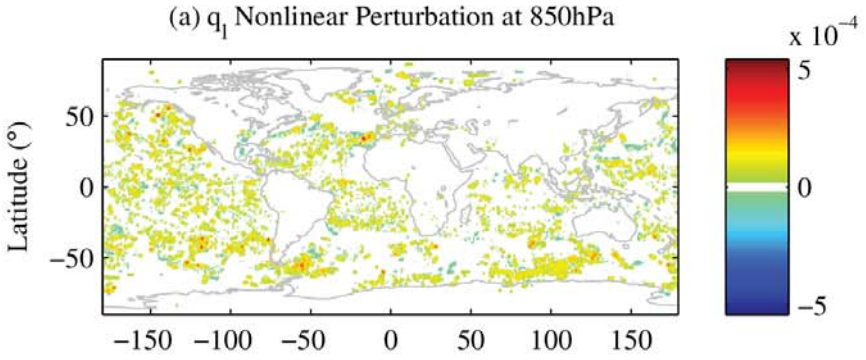
Very large perturbations occur around the calculation of cloud fraction when using PDF approach. We develop two approaches to dealing with this:

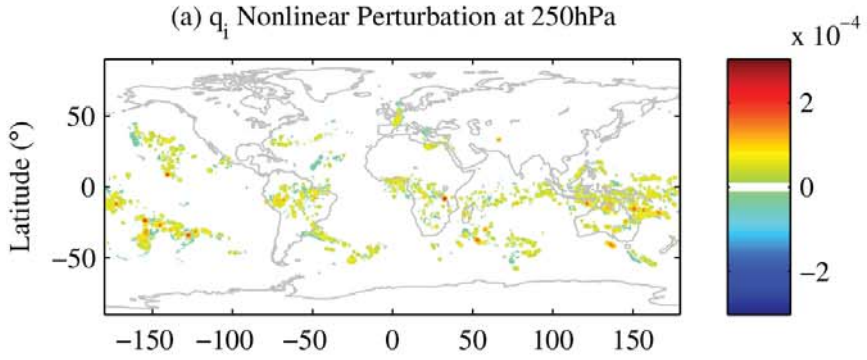
- Perturbation model approach for use in 4DVAR
- Filtering + perturbation model for use in observation impacts

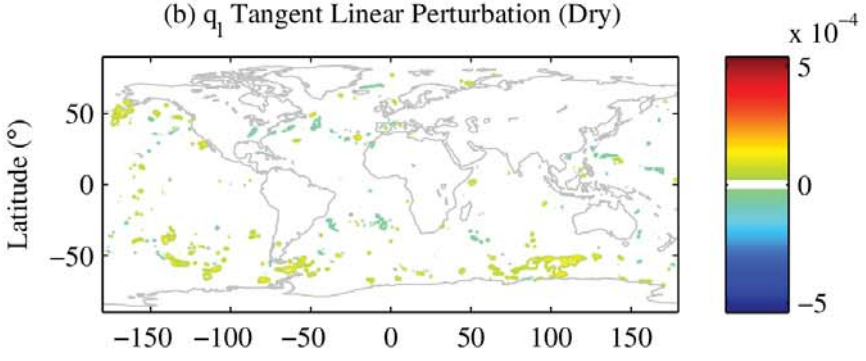
Large scale cloud source perturbation model

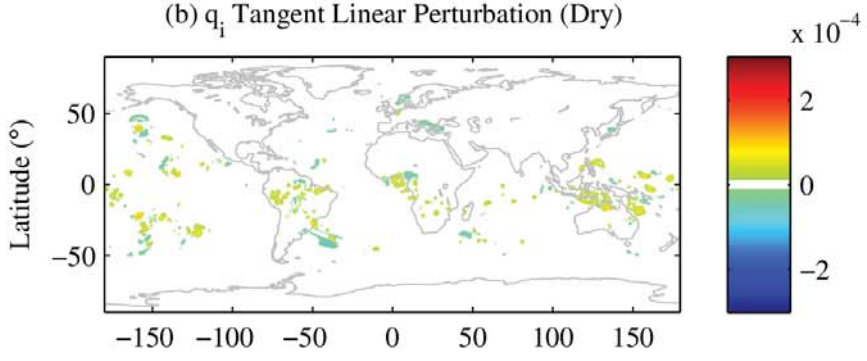


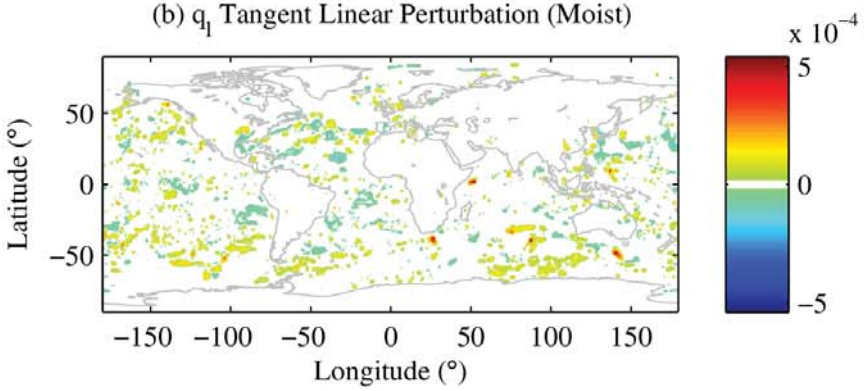
6-hour cloud perturbations

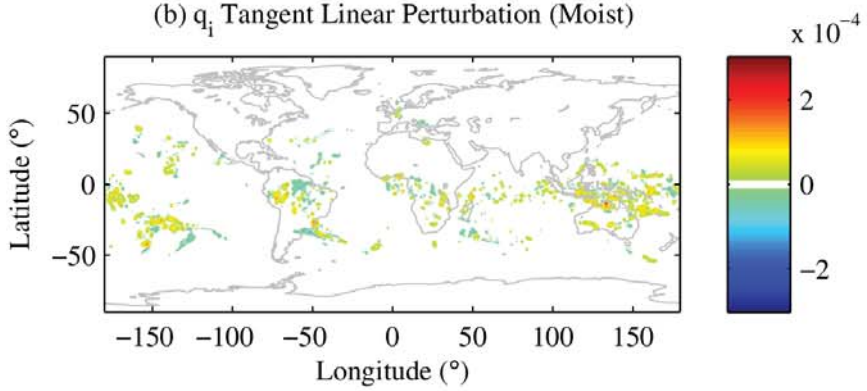






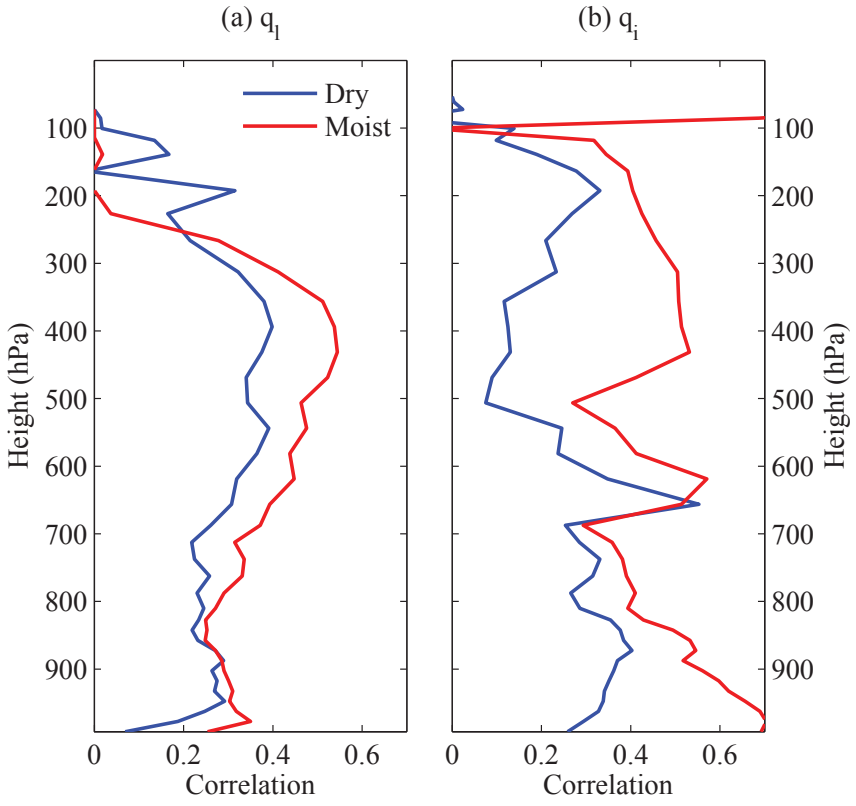




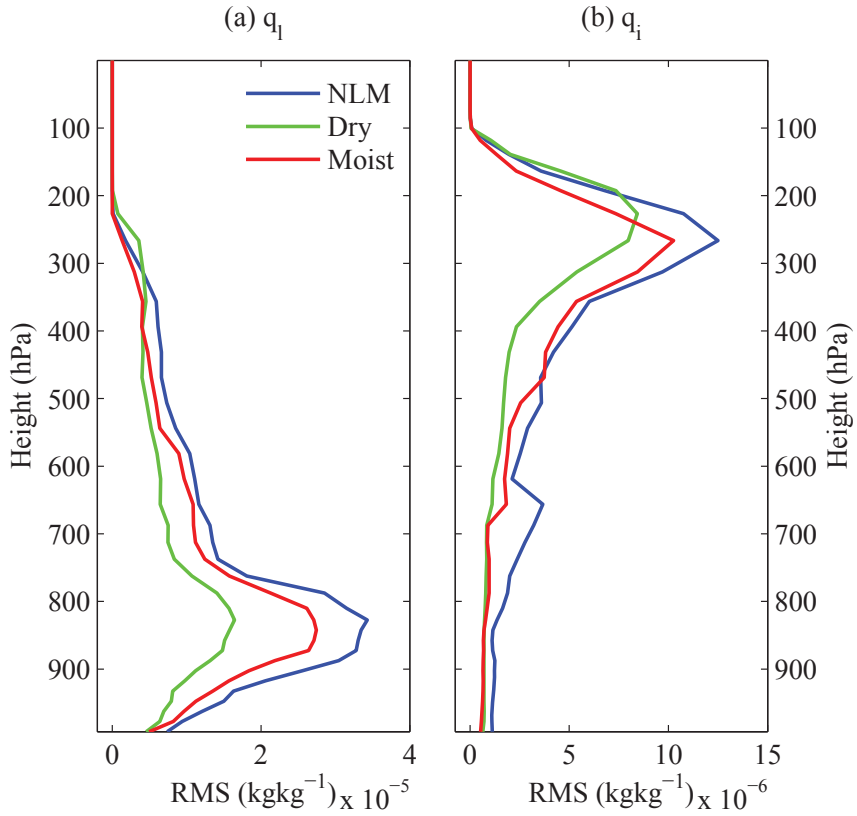


6-hour correlations and RMS

Correlations



RMS



Filtering

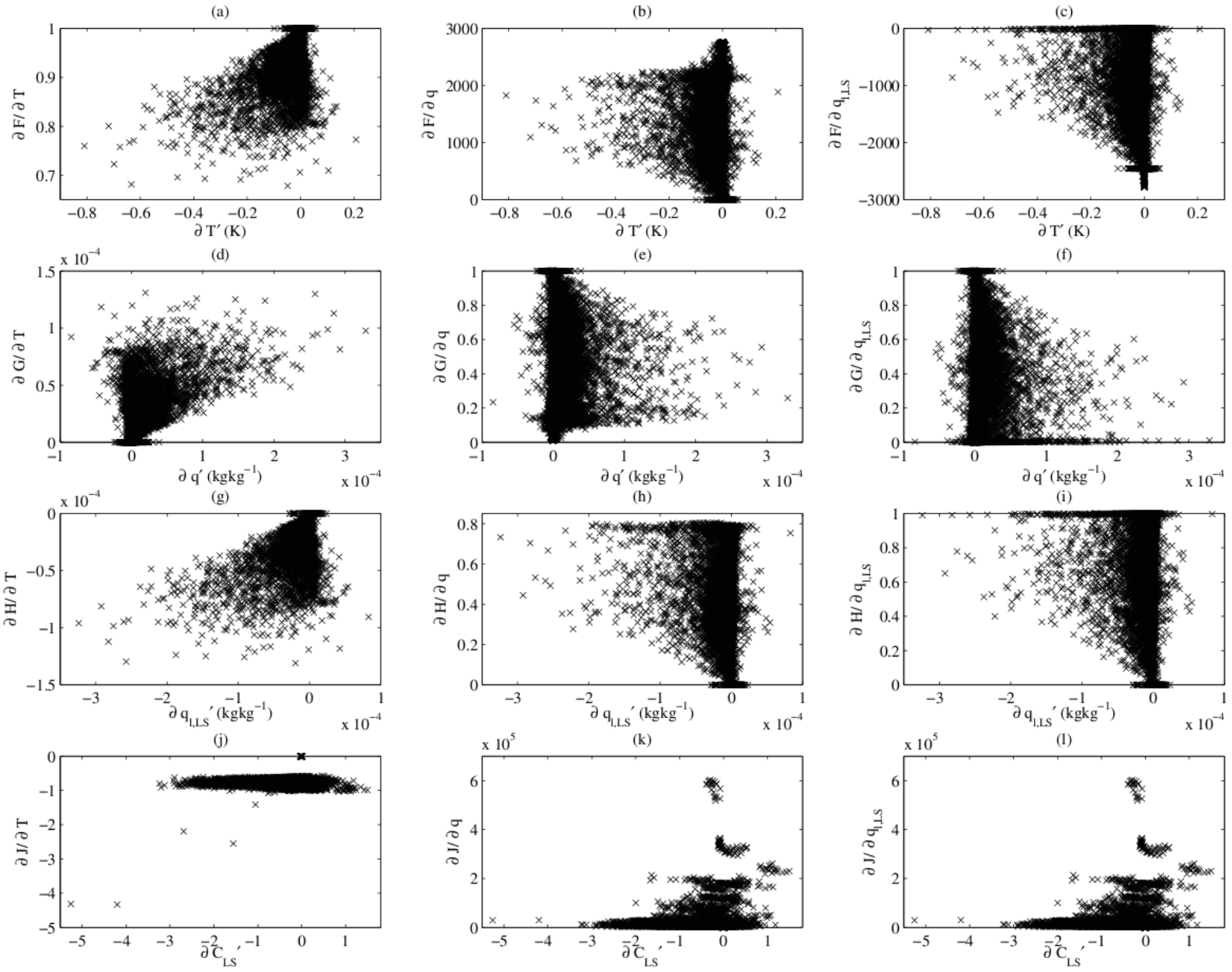
The perturbation model does not perform well for longer than a 12-hour integration. Large perturbation growth vs. way too diffusive.

Filtering developed based on examining the Jacobian of just the large scale source routine.

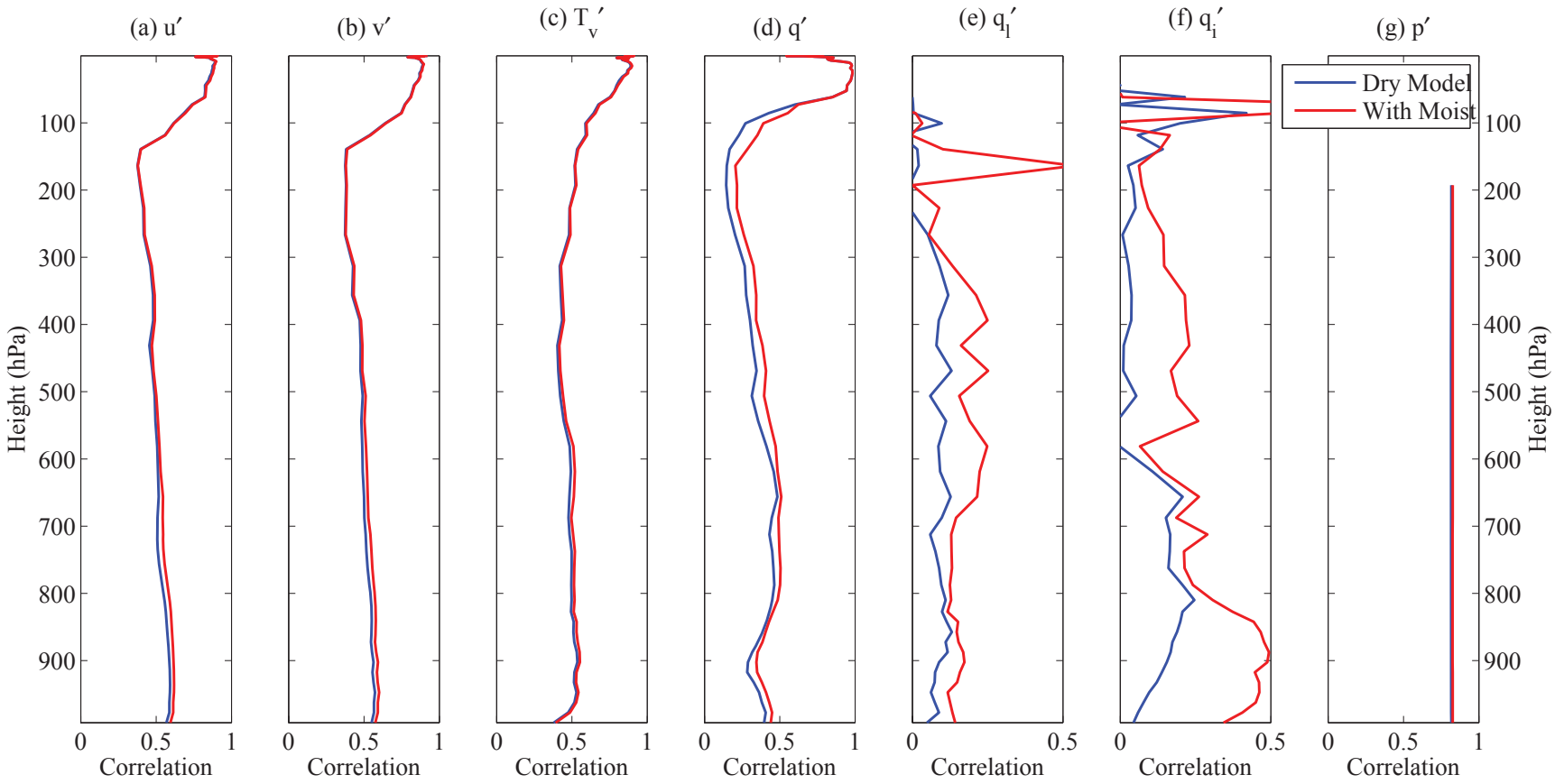
$$\begin{pmatrix} T' \\ q' \\ q'_{l,\mathrm{LS}} \\ q'_{i,\mathrm{LS}} \\ C'_{\mathrm{LS}} \end{pmatrix} = \begin{pmatrix} \frac{\partial F}{\partial T} & \frac{\partial F}{\partial q} & \frac{\partial F}{\partial q_{l,\mathrm{LS}}} & \frac{\partial F}{\partial q_{i,\mathrm{LS}}} \\ \frac{\partial G}{\partial T} & \frac{\partial G}{\partial q} & \frac{\partial G}{\partial q_{l,\mathrm{LS}}} & \frac{\partial G}{\partial q_{i,\mathrm{LS}}} \\ \frac{\partial H}{\partial T} & \frac{\partial H}{\partial q} & \frac{\partial H}{\partial q_{l,\mathrm{LS}}} & \frac{\partial H}{\partial q_{i,\mathrm{LS}}} \\ \frac{\partial I}{\partial T} & \frac{\partial I}{\partial q} & \frac{\partial I}{\partial q_{l,\mathrm{LS}}} & \frac{\partial I}{\partial q_{i,\mathrm{LS}}} \\ \frac{\partial J}{\partial T} & \frac{\partial J}{\partial q} & \frac{\partial J}{\partial q_{l,\mathrm{LS}}} & \frac{\partial J}{\partial q_{i,\mathrm{LS}}} \end{pmatrix}^{(r)} \begin{pmatrix} T' \\ q' \\ q'_{l,\mathrm{LS}} \\ q'_{i,\mathrm{LS}} \end{pmatrix},$$

Filter based on magnitudes of the elements and eigenvalues.

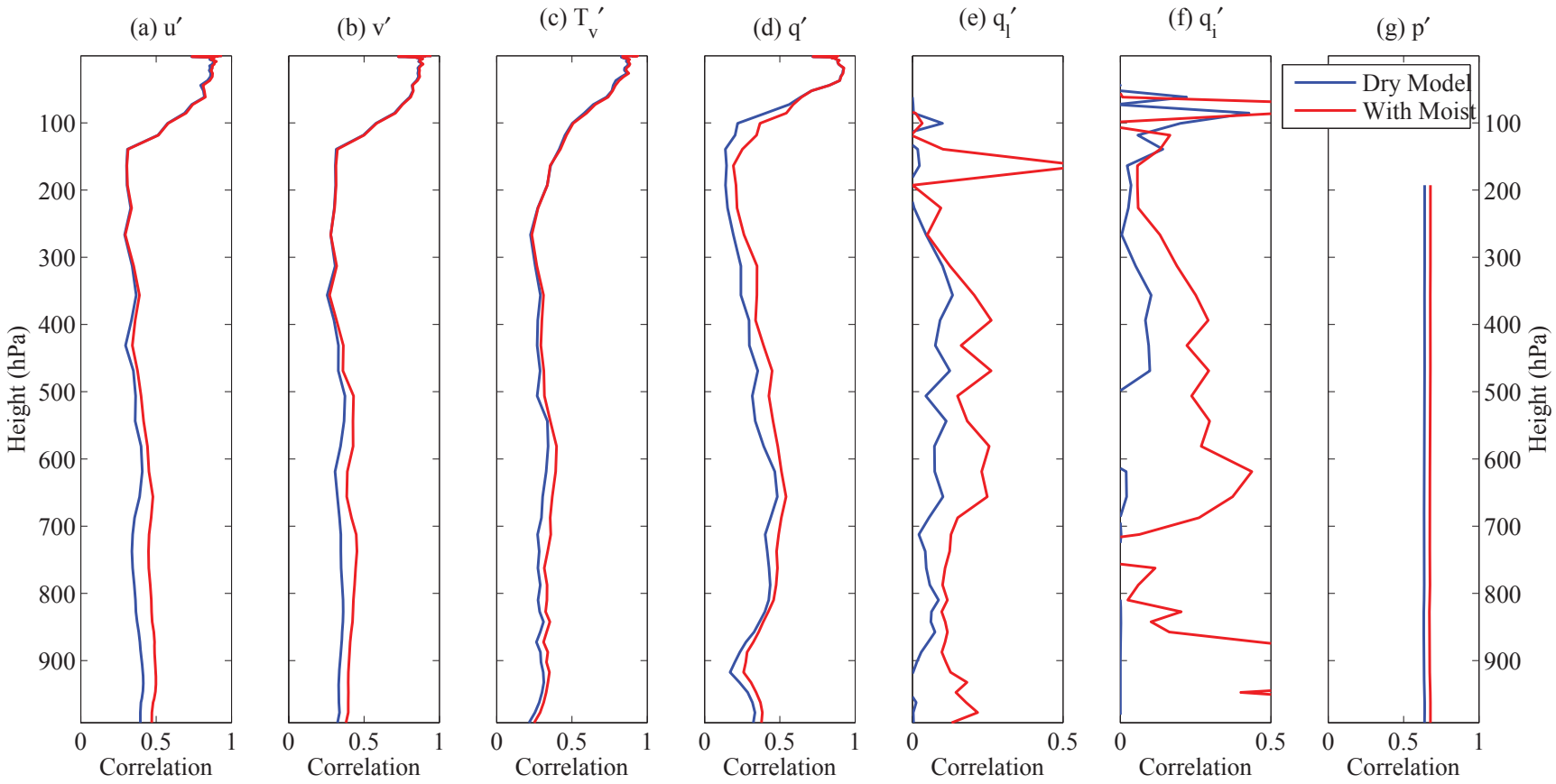
Jacobian correlations



24-hour correlations - Global



24-hour correlations - Tropics



Radiation

Solar and infrared radiation is now an option in the linear model.

Derived exactly from nonlinear code so slow, for the adjoint it's more expensive than the dynamics!

- Connected to clouds mass and fraction but not precipitation.
- Ozone is only active chemistry, CO_2 global constant.
- Option to include dust but 5 bins so really slow all round.

...nothing to see here...

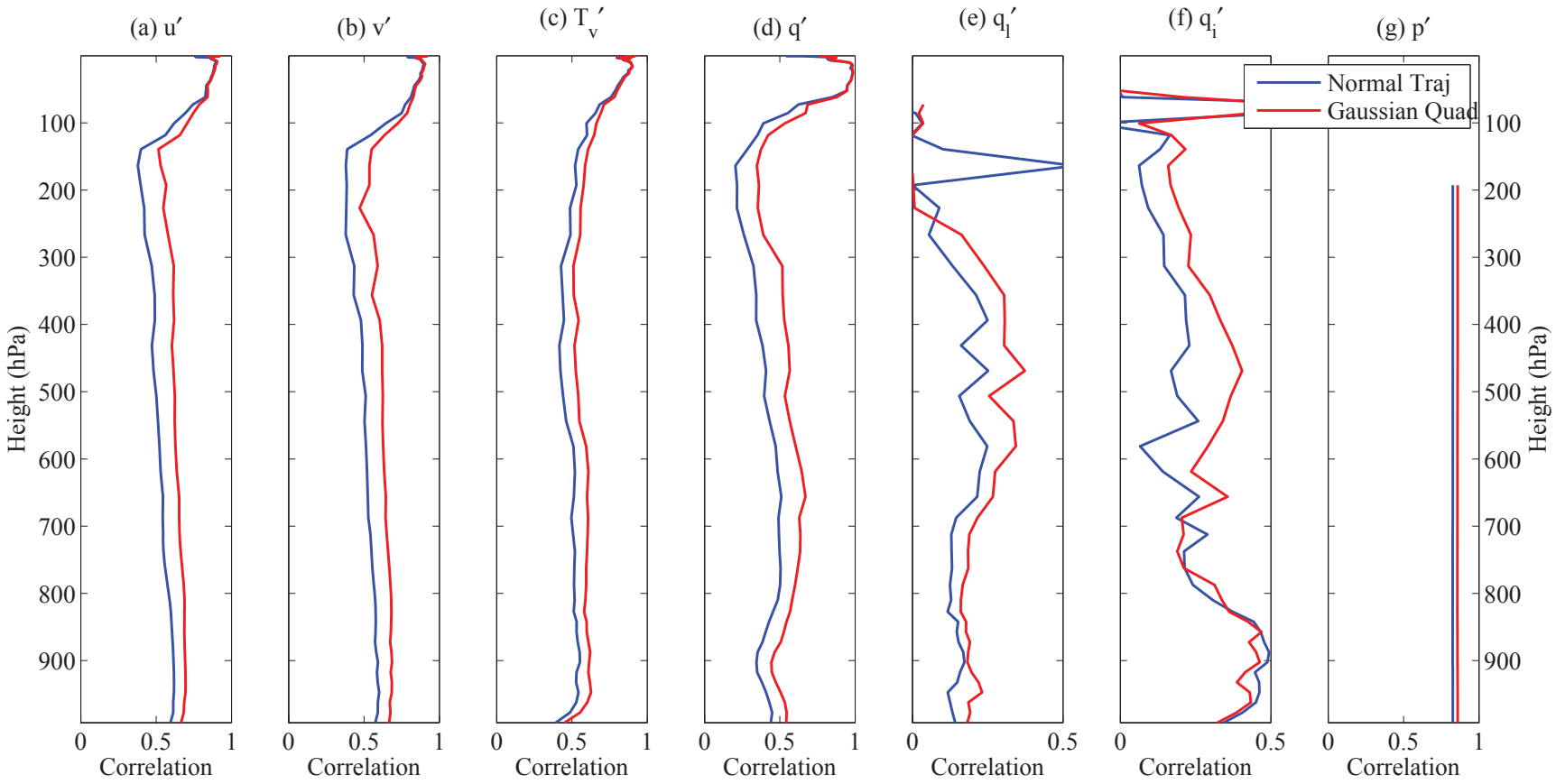
Gaussian quadrature - Rahul Mahajan

Observation impacts at GMAO are computed using two adjoint sensitivities. Linearized around forecasts initialized with the background and analysis.

Using Guassian quadrature the adjoint is linearized around an average of the two.

- Improves correlations for 24-hour forecasts.
- Extends linear validity to 48-hours so we can do longer observation impacts.

24-hour correlations w/ Gaussian quadrature



Adjoint sensitivity case studies

Interested in using the adjoint to analyse:

- Predictability of storm track and intensification (Brett Hoover)
- The role of dust in TC development (NAMMA period)
- Sudden stratospheric warming (Jan. 2013 and Jan. 2009)

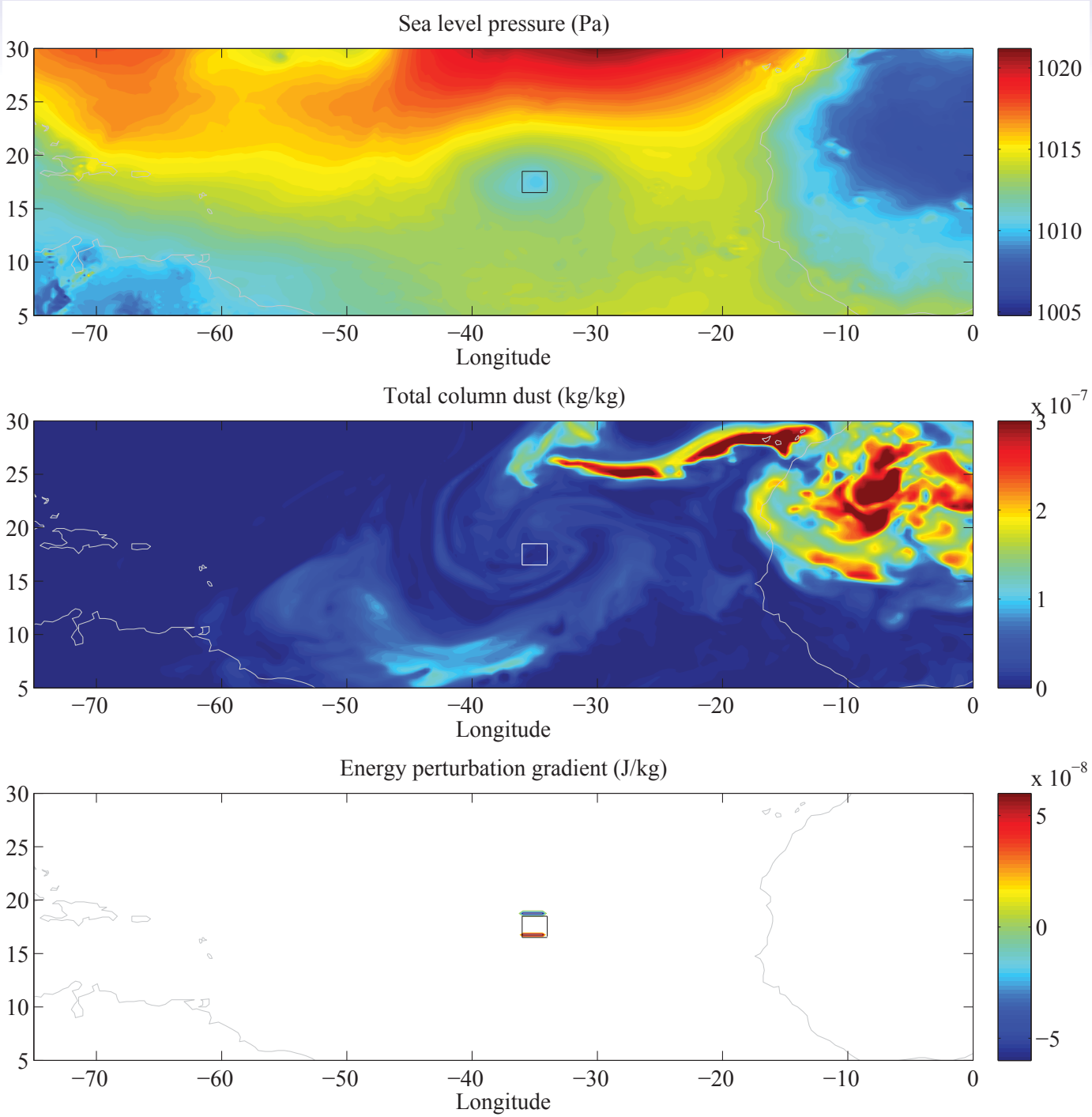
Dust Case Study

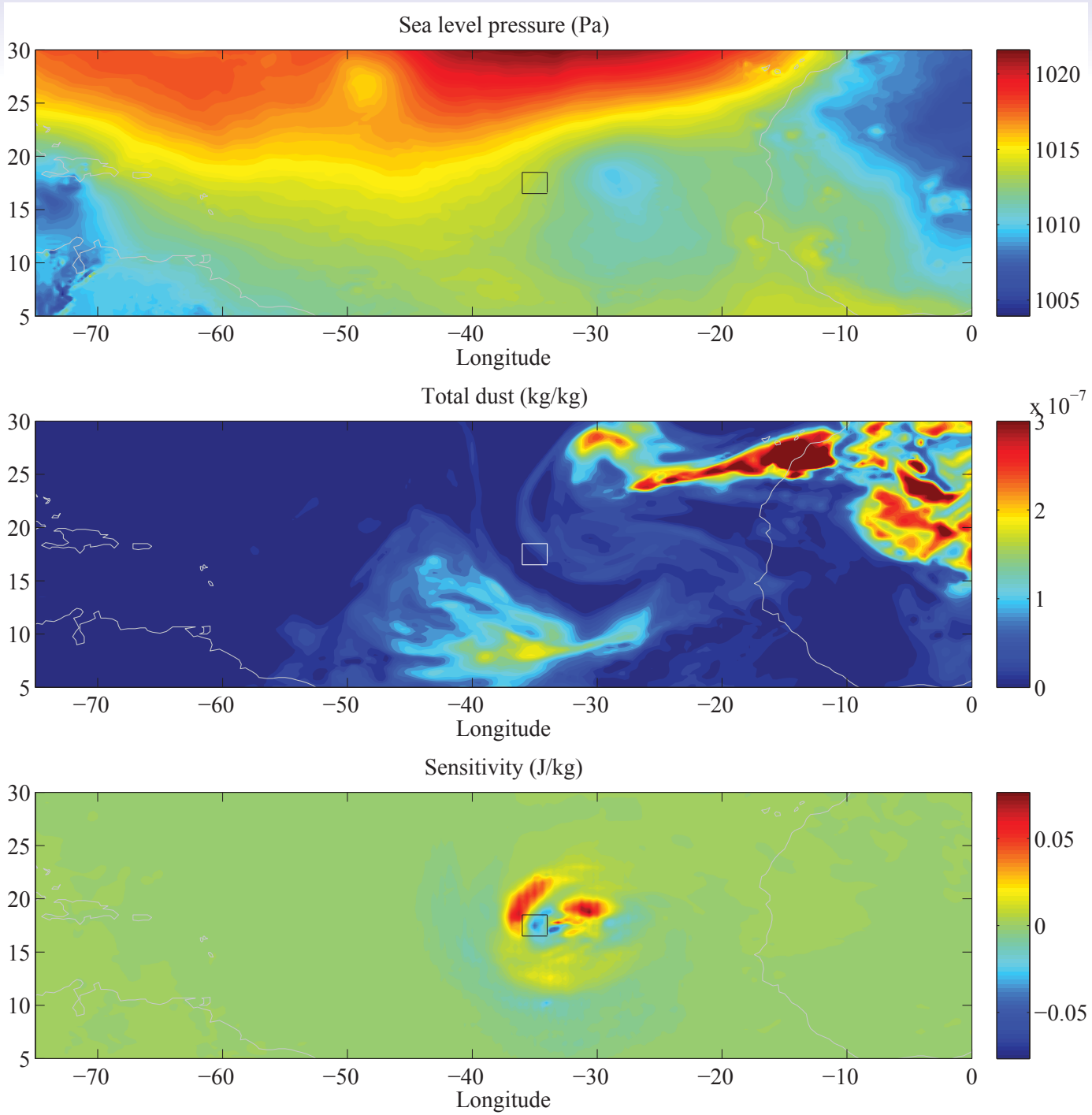
The development of linearized radiation enables the investigation of sensitivity to aerosols.

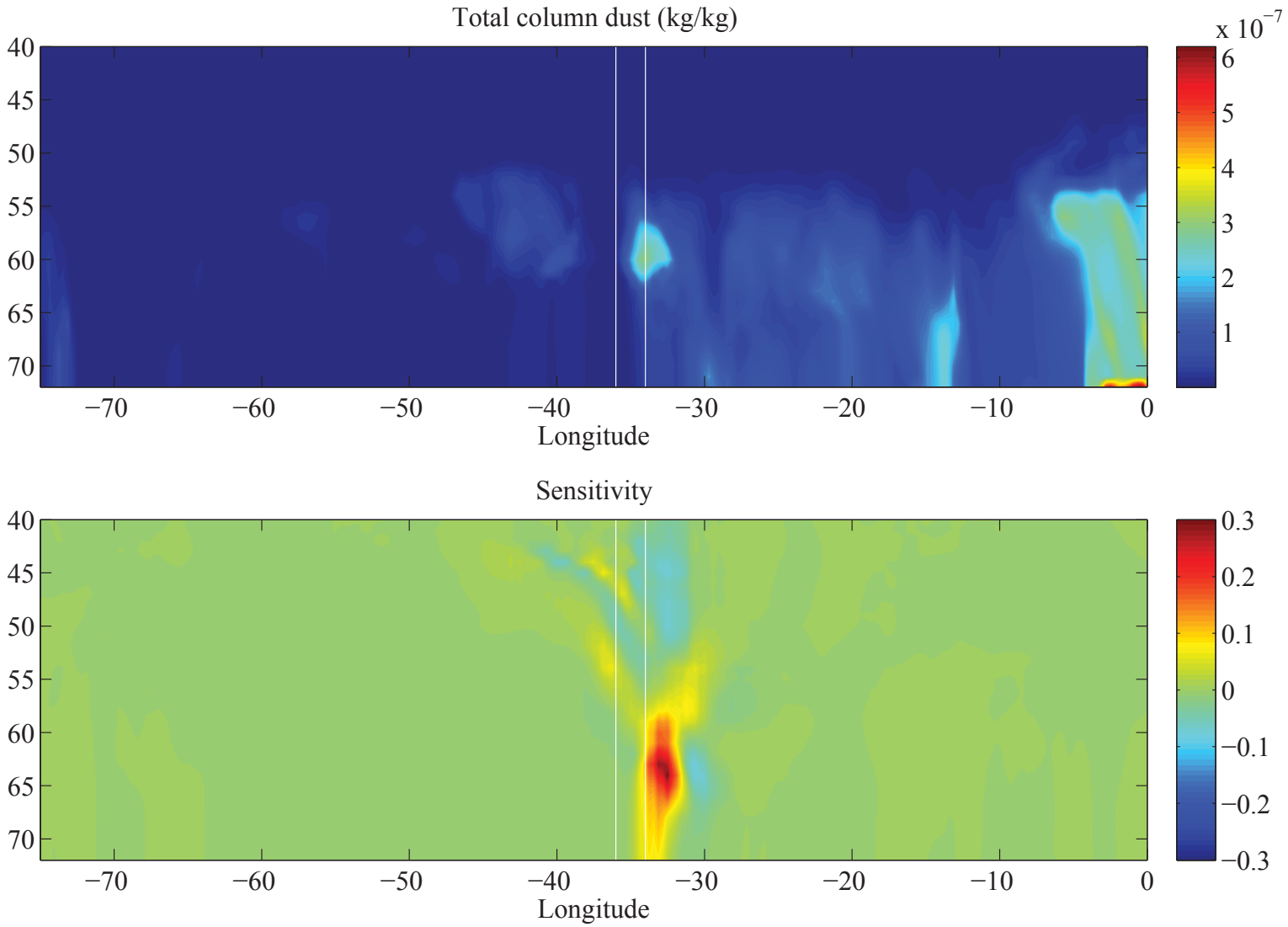
- NAMMA period mid August to mid September 2006
- Significant dust outbreaks combined with TC cyclogenesis
- Significant debate over the role that dust plays.
- Particular interest in hurricane Helene

Start by examining the following:

- August 27th 00z to August 28th 00z.
- Forecasts and adjoint at C360 (25km) with linear radiation.
- Currently no linear GOCART.


Sea level pressure (Pa)
30
25
20
15
10
5
−70
−60
−50
−40
−30
−20
−10
0
Longitude
1020
1015
1010
1005
Total column dust (kg/kg)
x 10^−7
3
2
1
0
Energy perturbation gradient (J/kg)
x 10^−8
5
0
−5


Sea level pressure (Pa)
30
25
20
15
10
5
−70
−60
−50
−40
−30
−20
−10
0
Longitude
1020
1015
1010
1005
Total dust (kg/kg)
x 10^−7
3
2
1
0
Sensitivity (J/kg)
0.05
0
−0.05


Total column dust (kg/kg)
x 10^−7
6
5
4
3
2
1
40
45
50
55
60
65
70
−70
−60
−50
−40
−30
−20
−10
0
Longitude
Sensitivity
0.3
0.2
0.1
0
−0.1
−0.2
−0.3
40
45
50
55
60
65
70
−70
−60
−50
−40
−30
−20
−10
0
Longitude

Conclusions

- Improvements to the current dynamics and boundary layer scheme.
- Significant speed up of convection by moving from Taf to Tapenade.
- Linear clouds in and working. Next step is all-sky assimilation (Min-Jeong Kim @ AGU).
- Radiation with dust.
- Have the confidence to look at some sensitivity studies.

- ...But question remains over advection, would like to improve.

Questions